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Notch Ductility Degradation of Low Alloy Steels with Low-to-Intermediate Neutron Fluence Exposures

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20. Abstract (Continued)

The steels with high radiation sensitivity indicated an onset of notch ductility change at fluences of $\sim 1.5 \times 10^{18}$ n/cm^2 by an elevation in the ductile-to-brittle transition temperature. Reductions in upper shelf were not observed at this fluence level but were in the range of 0 to 15% at $\sim 4 \times 10^{18}$ n/cm^2 and between 15 to 44% at $\sim 8 \times 10^{18}$ n/cm^2. The data trend suggests a power law relationship of upper shelf reduction to fluence at low-to-intermediate fluences.

The C_v transition temperature elevation and upper shelf reduction with irradiation are compared to embrittlement projections by U.S. Nuclear Regulatory Commission Guide 1.99. A limited experimental comparison of radiation effects to dynamic fracture toughness and notch ductility is also presented.

CONTENTS

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INTRODUCTION

The embrittlement of reactor structural steels by neutron fluence typically is assessed from changes in Charpy-V (C_v) notch ductility. The progressive increase in embrittlement with neutron exposure is known to be non-linear with fluence ($n/cm^2 > 1$ MeV) and, in addition, has been shown to be dependent on the content of copper and phosphorus impurities in the steel. Through C_v data compilations and analyses, radiation embrittlement trends have been evolved for application in reactor vessel design and for guidance of fracture safe vessel operation. One example of the development of embrittlement versus fluence curves is the U. S. Nuclear Regulatory Commission (NRC) Guide 1.99 [1]. While significant progress has been made, trend development efforts have been impeded greatly by a lack of radiation data for the extremes of the fluence range of interest. Projected end-of-life (EOL) fluences for many currently operating reactor vessels are on the order of 3 to 5 $\times$ 10^{19} n/cm^2. A large volume of data exists for 2 to 4 $\times$ 10^{19} n/cm^2 fluences; however, data for exposures below this fluence interval are scarce. This study was undertaken with the objective of improving knowledge of both the extent and trend of C_v notch ductility changes in reactor vessel steels (plate and weld metals) at low-to-intermediate fluences, that is, between 0.1 and 1 $\times$ 10^{19} n/cm^2. A second objective was to obtain an experimental assessment of the level of conservatism in current embrittlement projection methods.

Property changes at less than EOL fluences have become of increasing importance as a result of minimum notch ductility levels set forth in the Code of Federal Regulations (10CFR50) [2] and the ASME Code, Section III [3]. A C_v upper shelf energy level of at least 68 J (50 ft-lb), for example, is required to index the reference nil ductility temperature, RT_{NDT}, for fracture toughness characterization of the vessel material. Additional considerations are recommendations and specifications for the selection of reactor vessel surveillance materials [2,4]. For surveillance, the materials normally included in the program are those predicted to be most limiting with regard to the setting of pressure-temperature limits for fracture safe operation. Here, it is conceivable that the materials with the highest fluence accumulation may not always be the limiting materials because of radiation sensitivity differences. Therefore knowledge of radiation effects to a spectrum of materials for fluence conditions less than the vessel beltline fluence is important.

MATERIALS

Several commercially produced plates and weld deposits were selected for the investigation. The materials are identified by NRL code number and composition in Table 1 and are fully representative of reactor vessel materials now in service. The A302-B plate is also the ASTM reference correlation-monitor steel used extensively in reactor surveillance programs [5].

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Table 1 — Test Materials[a]

Material	NRL Code	Chemical Composition, wt%										
		Cu	P	C	Mn	S	Si	Ni	Cr	Mo	V	Other
A302-B Plate[b]	F26	0.20	0.011	0.24	1.34	0.023	0.23	0.18	0.11	0.51	0.01	Al 0.038
A533-B Plate	N27[c]	0.13	0.008	0.17	1.21	0.007	0.20	0.56	—[d]	0.50	0.02	Al 0.015
	EBB	0.10	0.009	0.19	1.28	0.013	0.25	0.61	0.04	0.55	0.004	
	EDB	0.14	0.009	0.20	1.31	0.012	0.22	0.62	0.08	0.59	0.004	
	3MU[e]	0.12	0.011	0.20	1.26	0.018	0.25	0.56	0.10	0.45	—	Al 0.034
A533-B S/A Weld	MY	0.36	0.015	0.14	1.38	0.012	0.22	0.78	0.07	0.55	—	
	W1	0.35	0.020	0.09	1.45	0.013	0.68	0.57	—	0.39	—	
	NRL 1	0.19	—	—	1.43	—	—	0.56	0.08	0.36	—	
	NRL 2	0.29	—	—	1.56	—	—	0.65	0.08	0.39	—	
	NRL 3	0.30	—	—	1.53	—	—	0.68	0.08	0.40	—	
	NRL 4	0.16	—	—	1.51	—	—	0.58	0.08	0.37	—	
	NRL 5	0.39	—	—	1.60	—	—	0.58	0.10	0.39	—	
	NRL 6	0.16	—	—	1.49	—	—	0.58	0.09	0.39	—	
	NRL 7	0.27	—	—	1.42	—	—	0.56	0.06	0.36	—	
	NRL 8	0.32	—	—	1.51	—	—	0.68	0.07	0.39	—	
	W	0.29	0.020	0.09	1.50	0.014	0.56	0.62	0.16	0.37	<0.01	
	62N(1)[f,g]	0.18	0.019	0.08	1.55	0.008	0.60	0.55	0.17	0.38	0.01	
	62N(2)[f]	0.24	0.013	0.08	1.42	0.008	0.57	0.50	0.07	0.37	0.01	
	63N[f]	0.31	0.017	0.10	1.62	0.010	0.65	0.69	0.09	0.42	0.01	

[a]Material thickness range: 15.2 to 26.6 cm
[b]ASTM A302-B Reference Plate [5]
[c]NRL A533-B Demonstration Melt [8]
[d]Not determined
[e]IAEA Reference Plate (HSST Plate 03)
[f]Approximate composition
[g]Two weld filler wires used

The C_v specimens (ASTM Specification E-23, Type A) were taken from the quarter thickness location in plates and from through-thickness locations in weld deposits. Specimens of the A-302-B and A533-B plates were oriented, respectively, to represent the longitudinal (LT) and transverse (TL) test orientations [6]. Weld metal specimens were oriented with their long axis perpendicular to the welding direction. In all cases, the axis of the specimen notch was perpendicular to the surface of the material.

A limited study of the irradiation effect to dynamic fracture toughness (K_J) was also accomplished using fatigue precracked Charpy-V (PCC_v) specimens and J-integral assessment methods. The K_J was computed from specimen energy absorption to maximum load corrected for specimen and test machine compliance. Electric Power Research Institute (EPRI) procedures and requirements for K_J determinations were satisfied [7].

MATERIAL IRRADIATION

Material irradiations (Table 2) were conducted at a nominal 288°C (550°F) at the State University of New York at Buffalo using its 2 MW pool reactor (UBR). Irradiation temperatures were monitored by multiple thermocouples in each specimen array. The ambient neutron flux was on the order of 7×10^{12} n/cm^2-sec. Fluence determinations were based on measurements with iron neutron dosimeter wires placed among the specimens. For the UBR fuel lattice positions used, the calculated spectrum fluence (Φ^{cs}) and the fluence based on an assumed fission spectrum (Φ^{fs}) have the relation:

$$\Phi^{cs} = 1.22\,\Phi^{fs}\ (> 1\ \text{MeV}). \tag{1}$$

Table 2 — Material Irradiation Experiments

Experiment No.	Target Fluence 10^{18} n/cm^2 > 1 MeV	Material Codes
1	1	Plates F26, N27, Weld MY
2	5	Plate N27, Weld MY
3	7	Welds W, 62N(1), 63N
4	10	Weld 62N(1)
5	1	Plates EBB, EDB, Weld W1
6	3	Welds NRL 1 to NRL 5, NRL 7, NRL 8
7	6	Welds NRL 1 to NRL 5, NRL 7, NRL 8
8	11	Weld NRL 6
9	18	Plate 3 MU
(C_v, PCC_v)		

RESULTS

Experimental C_v results for the individual materials are illustrated in Figs. 1 through 17 and are summarized in Table 3. Fluences listed in each figure are calculated spectrum fluences (Φ^{cs}). In the discussion below, ductile-to-brittle transition behavior is indexed to the 41 J (30 ft-lb) temperature unless noted otherwise.

Table 3 — Summary of Charpy-V Notch Ductility Changes With 288°C (550°F) Irradiation

Material/Code	Fluence 10^{18} n/cm^2 (>1 MeV) (Φ^{cs})	Transition Temperature														Upper Shelf				
		Unirradiated				Irradiated								Unirradiated		Irradiated		
		C_v 41J		C_v 68J		C_v 41J				C_v 68J								
		°C	°F	°C	°F	°C	°F	Δ°C	Δ°F	°C	°F	Δ°C	Δ°F	J	ft-lb	J	ft-lb	ΔJ
A302-B Plate																		
F26	1.2	-18	0	10	50	4	40	22	40	32	90	22	40	117	86	117	86	0
A533-B Plate																		
N27	1.2	-62	-80	-43	-45	-62	-80	0	0	-40	-40	0	0	187	138	187	138	0
	6.6	-62	-80	-43	-45	-34	-30	28	50	-9	15	33	60	187	138	171	126	16
	21.0[a]	-62	-80	-43	-45	16	60	78	140	46	115	89	160	187	138	~134	~99	53
EBB	1.3	-12	10	13	55	<2	≤35	≤14	≤25	29	85	17	30	137	101	137	101	0
EDB	1.3	-1	30	21	70	18	65	19	35	41	105	19	35	160	118	160	118	0
3MU	17.0	-1	30	29	85	43	110	44	80	77	170	47	85	138	102	136	100	~0
S/A Weld																		
MY	1.2	-34	-30	-15	5	-4	25	31	55	21	70	36	65	145	107	142	105	~0
	6.6	-34	-30	-15	5	99	210	133	240	124	255	139	250	145	107	103	76	42
	26.0[a]	-34	-30	-15	5	141	285	175	315	174	345	189	340	145	107	76	56	69
W1	1.4	-29	-20	2	35	2	35	31	55	—	—	—	—	94	69	94	69	0
NRL 6	16.0	-23	-10	7	45	88	190	111	200	107	225	100	180	107	79	77	57	30
NRL 1[b]	4.2	-15	5	4	40	27	80	42	75	82	180	78	140	107	79	103	76	4
	9.5	-15	5	4	40	66	150	81	145	104	220	89	160	107	79	90	66	17
NRL 2	4.2	-34	30	41	105	57	135	58	105	96	205	56	100	104	77	91	67	13
	9.5	-34	30	41	105	93	200	94	170	129	265	89	160	104	77	81	60	23
NRL 3	3.9	-9	15	27	80	57	135	67	120	93	200	67	120	100	74	96	71	4
	8.5	-9	15	27	80	85	185	94	170	121	250	94	170	100	74	81	60	19
NRL 4[b]	3.6	-18	0	18	65	27	80	44	80	46	115	28	50	98	72	90	66	8
	7.6	-18	0	18	65	52	125	69	125	77	170	58	105	98	72	76	56	22
NRL 5	3.9	16	60	52	125	-1	30	53	95	113	235	61	110	83	61	83	61	0
	9.0	16	60	52	125	88	190	72	130	127	260	75	135	83	61	79	58	4
NRL 7	3.2	-26	-15	7	45	13	55	39	70	49	120	42	75	111	82	106	78	5
	6.7	-26	-15	7	45	43	110	69	125	79	175	72	130	111	82	90	66	21
NRL 8[b]	3.9	-9	15	24	75	63	145	72	130	93	200	69	125	106	78	90	66	16
	9.0	-9	15	24	75	91	195	100	180	116	240	92	165	106	78	79	58	27
W	8.9	-29	-20	-1	30	60	140	89	160	—	—	—	—	104	77	65	48	39
62N(1)	8.9	-29	-20	4	40	60	140	89	160	102	215	97	175	103	76	79	58	24
	12.1	-29	-20	4	40	71	160	100	180	—	—	—	—	103	76	68	50	35
63N	7.8	4	40	~38	~100	135	275	131	235	—	—	—	—	87	64	49	36	38

[a]Prior data.
[b]Upper shelf values taken at 160°C (320°F).

Observations for 1 to 2 $\times$ 10^{18} n/cm^2

Figures 1 through 6 present data for the low fluence condition. The results indicate that radiation effects on notch ductility are first becoming significant at this fluence level. Transition temperature increases are on the order of 14 to 31°C (25 to 55°F) with the highest copper content materials (welds MY and W1) showing the greatest irradiation effect. In contrast, upper shelf reductions are notably absent. It thus appears that the transition temperature elevation begins with fluence in advance of the upper shelf reduction and that the mechanisms responsible for each are not the same.

In Figs. 2 and 5, a higher neutron exposure of 6.6 $\times$ 10^{18} n/cm^2 (intermediate fluence level) is found to produce both a transition temperature elevation and an upper shelf decrease in plate and weld material. The weld shows a much greater irradiation effect than the plate and this is a direct consequence of its higher copper content. Further irradiation to ~2 $\times$ 10^{19} n/cm^2, on the other hand, produced a similar increase in transition temperature for the plate and the weld, that is, 50°C vs 42°C. Nonetheless, the overall radiation sensitivity of the weld is much greater than that of the plate.

Referring to Fig. 1 (ASTM reference plate), the upper graph shows unirradiated condition test results obtained for the plate at a location displaced from the location of the irradiation test specimens. In the lower graph, results obtained from "control specimens" from the same location as the irradiated specimens are indicated and illustrate the importance of making property checks in critical testing. Referencing the control data, a 22°C transition temperature elevation is measured. A shift of $\leq$11°C (insignificant) would be measured relative to the mean of the data band. Obviously, inappropriate unirradiated condition data can inject not only scatter, but also considerable confusion into radiation trend analyses. Moreover, it is seen that "errors" in reference condition properties have the potential for masking the benefit of refinements in experimental procedures, including dosimetry.

Observations for 3 to 4.5 $\times$ 10^{18} n/cm^2

In this fluence interval, both a transition temperature elevation and an indication of upper shelf reduction were observed for all but one (Weld NRL 5) of the materials tested. Tests of the plates were not conducted in this range; however, a prior evaluation of the ASTM reference plate at 5.5 $\times$ 10^{18} n/cm^2 [5] produced a 36°C (65°F) transition increase. (Upper shelf level was not established). Smaller transition increases would be projected for the other, lower copper content plates. Overall, transition temperature elevations ranged from about 39 to 100°C (70 to 180°F). Upper shelf reductions ranged from 0 to 15%.

The irradiation effect is generally found proportional to material copper content. The nonconformance of Weld NRL 5 to this pattern at this fluence level is being investigated. No explanation can be offered at this time.

Observations for 6.5 to 9.5 $\times$ 10^{18} n/cm^2

Here, large transition temperature elevations ranging from 69 to 133°C (125 to 240°F) were observed for the welds along with large reductions in upper shelf energy (15 to 44%). A greater radiation resistance was found for plate N27 and would be characteristic of companion plates of the same general copper content [8]. Of special interest, Figs. 7 and 8 demonstrate that upper shelf levels can be reduced to 68 J (50 ft-lb) or lower at this intermediate fluence level. In the case of weld 63N (Fig. 8), the upper shelf was reduced to 49 J (36 ft-lb) by 7.8 $\times$ 10^{18} n/cm^2. Isolation of the metallurgical reason(s) for such poor upper shelf retention should be an urgent task. Nonetheless, the results show the need for evaluations of intermediate fluence effects as well as EOL fluence effects in developing embrittlement projections.

Observations for > 10 $\times$ 10^{18} n/cm^2

A few of the materials were irradiated to fluences greater than 10 $\times$ 10^{18} n/cm^2. The data, given in Figs. 2, 5, and 9, indicate a trend of increasing radiation embrittlement with increasing fluence but at a much reduced rate. This is most evident in Fig. 5 and is consistent with earlier findings [5,8,9]. On this point, a large volume of data from test reactor irradiations exist for > 2 $\times$ 10^{19} n/cm^2 fluences which clearly show increasing radiation effects with fluence. For surveillance irradiations, on the other hand, recent data by Westinghouse suggest a saturation of radiation effects at ~1 $\times$ 10^{19} n/cm^2 when the flux is low, ~5 $\times$ 10^{10} n/cm^2-sec [10]. Confirmatory research, however, is clearly needed. For one, a closely controlled set of test reactor experiments should be performed to verify the suggested saturation, using flux and fluence levels comparable to those of the power reactor results. Secondly, higher fluence irradiations will be important to confirm that the effect is not temporary, that is, restricted to a certain fluence interval only, since EOL fluences can be high. It is noted in Fig. 9 that the increased embrittlement can almost be masked by data scatter when the increment of additional fluence is small, such as 3 $\times$ 10^{18} n/cm^2.

Trend of Upper Shelf Reduction at Low-to-Intermediate Fluence

Analysis of the data relating percentage upper shelf reduction and fluence for the weld metals in the low-to-intermediate fluence interval suggests a relationship of the form:

$$\text{Upper Shelf Reduction (\%)} = A(\Phi^{cs})^n,$$

where A and n are constants for a material. The value of A varies with material and is an indicator of material radiation sensitivity. The exponent, n, on the other hand, appears relatively material independent and has a value of about 2.3. Welds NRL 2 and NRL 8 which exhibited the largest upper shelf reduction of the materials at 4 $\times$ 10^{18} n/cm^2 depart from the primary data pattern. In these two cases, lower values of n are required to fit the data. Investigations to further explore the trend relationship are in progress.

Fracture Toughness (K_J) Degradation

A limited investigation of relative fracture toughness degradation with irradiation was conducted using the IAEA reference plate (HSST Plate 03, NRL Code 3MU). The PCC_v specimens and C_v specimens were commingled in the irradiation assembly to achieve an identical exposure history. The results, given in Fig. 18, show a good agreement of transition temperature elevations measured by the two test methods. Evidence of a possible correlation of PCC_v and C_v results have also been found by an EPRI-NRL research program on A533-B steel [11]. One plate, for example, exhibited an increase in C_v 41 J temperature of 92°C (165°F) and an increase in 100 MPa$\sqrt{m}$ temperature of 86°C (155°F) after ~3 × 10^{19} n/cm^2 at 288°C (550°F). If the tentative correlation is confirmed by additional PCC_v tests now in progress and by dynamic compact toughness tests, the value of the large volume of C_v irradiation data generated in prior years will be greatly enhanced.

DISCUSSION

Graphs given by the NRC Guide 1.99 for the projection of C_v notch ductility changes with fluence are reproduced in Figs. 19 and 20. Both figures take into account the role of impurity copper and phosphorus contents in radiation sensitivity development. One objective of the present study was to test the conservatism of NRC Guide projections in the low-to-intermediate fluence range, recognizing that only sparse data were previously available for defining property-change limits in this interval. Entry of the new data on the graphs indicates that the NRC Guide may be overly conservative in projecting upper shelf reductions at low fluences and at intermediate fluences. A lesser degree of overconservatism is noted for its transition temperature projections.

In Fig. 19, the data suggest that upper shelf change might be more accurately described by a set of bilinear curves such as used to project transition temperature behavior (see Fig. 20). Similar evidence from surveillance programs, however, would be required before new curves could be promulgated. Unfortunately, surveillance data appear to be more scattered in this format and are illustrative of a broad range of performance at low fluences. One source of scatter has been discussed with the ASTM reference plate results (Fig. 1). Appreciable reductions in upper shelf have also been observed for some long term reactor surveillance irradiations to further cloud the analysis.

In Fig. 21, measured and projected transition temperature increases are compared. Here, a broad scatter is evident, particularly at the higher embrittlement levels. The source of the scatter has not been established but may be due partially to the lack of a term for nickel content in the projection formula. That is, data are available which indicate that nickel content can cause a reenforcement of the primary copper content effect on radiation sensitivity [12,13].

To summarize, the new data suggest that current penalties at low fluence could be reduced provided that reasons for inconsistencies in surveillance data become understood. The possibility for a reduced penalty appears to be greatest for upper shelf energy properties.

CONCLUSIONS

Charpy-V notch ductility changes produced by low-to-intermediate neutron fluences at 288°C (550°F) have been investigated using several plate and weld metals representative of reactor vessel construction. The irradiation effect in general was found to increase with material impurity copper content. Primary observations and conclusions of the study were the following:

1. At low fluences of 1 to 2 $\times 10^{18}$ n/cm^2, high radiation sensitive steels begin to exhibit changes in notch ductility. Transition temperature elevations in excess of 11°C (20°F) but not upper shelf reductions were observed at this fluence level.

2. Fluences of 3 to 4.5 $\times 10^{18}$ n/cm^2 produced transition temperature elevations of 39 to 100°C (70 to 180°F) and upper shelf reductions of 0 to 15%.

3. At intermediate fluences of 6.5 to 9.5 $\times 10^{18}$ n/cm^2, large transition temperature elevations of 69 to 133°C (125 to 240°F) and large reductions in upper shelf energies of 15 to 44% were observed. One weld exhibited 49 J maximum after 7.8 $\times 10^{18}$ n/cm^2.

4. For low-to-intermediate fluences, a relationship of upper shelf reduction to fluence of the form: Reduction (%) = A $(\Phi^{cs})^n$, is suggested by the data for most of the materials. The value of A varies with material radiation sensitivity; the value of n is relatively material independent.

5. NRC Guide 1.99 may be overly conservative in projecting upper shelf reduction at fluences less than 5 $\times 10^{18}$ n/cm^2. A lesser degree of overconservatism was indicated by the data for transition temperature projection.

6. The trend of log percent upper shelf reduction with log neutron fluence appears best described by a set of bilinear curves.

7. A correlation between transition temperature elevations measured by dynamic PCC_v and C_v test methods appears possible from initial experimental comparisons.

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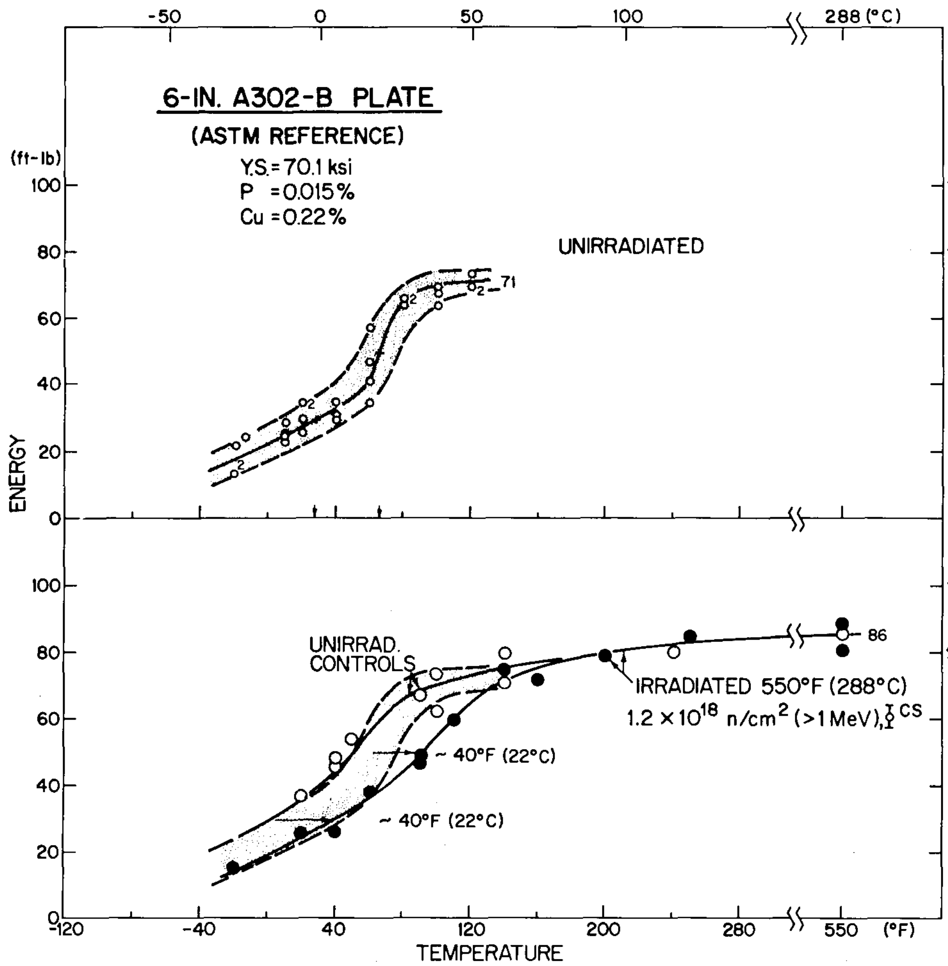

Fig. 1 — Charpy-V notch ductility of the ASTM A302-B reference plate. The upper graph shows baseline data for the plate. The lower graph compares control test results with results for low fluence irradiation. The baseline data band is also shown for reference.

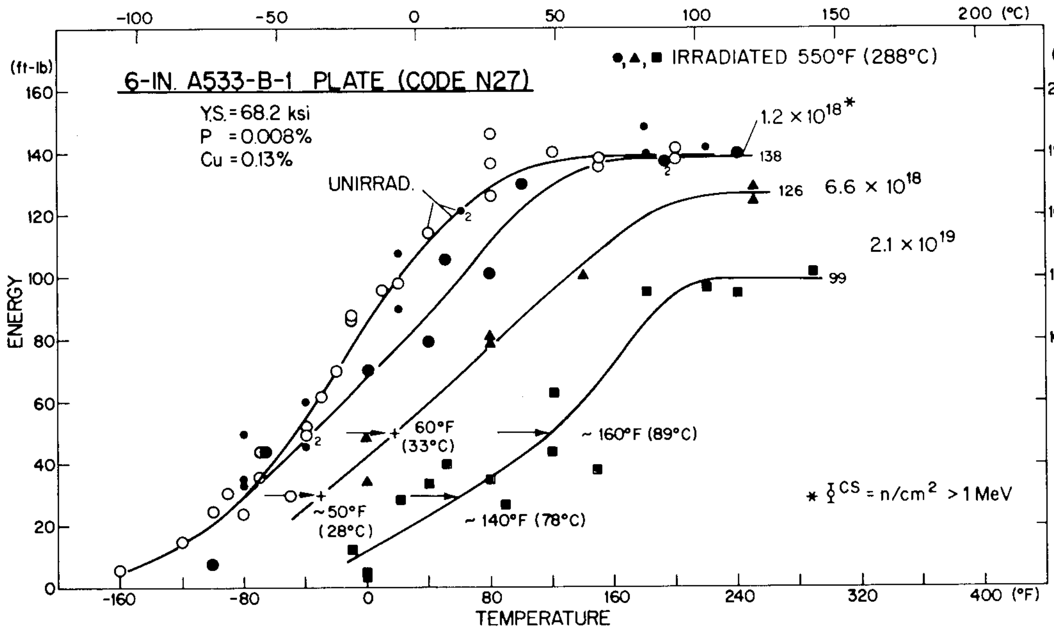

Fig. 2 — Charpy-V notch ductility of an A533-B plate, Code N27, from the NRL demonstration melt [8] before and after irradiation to three fluences

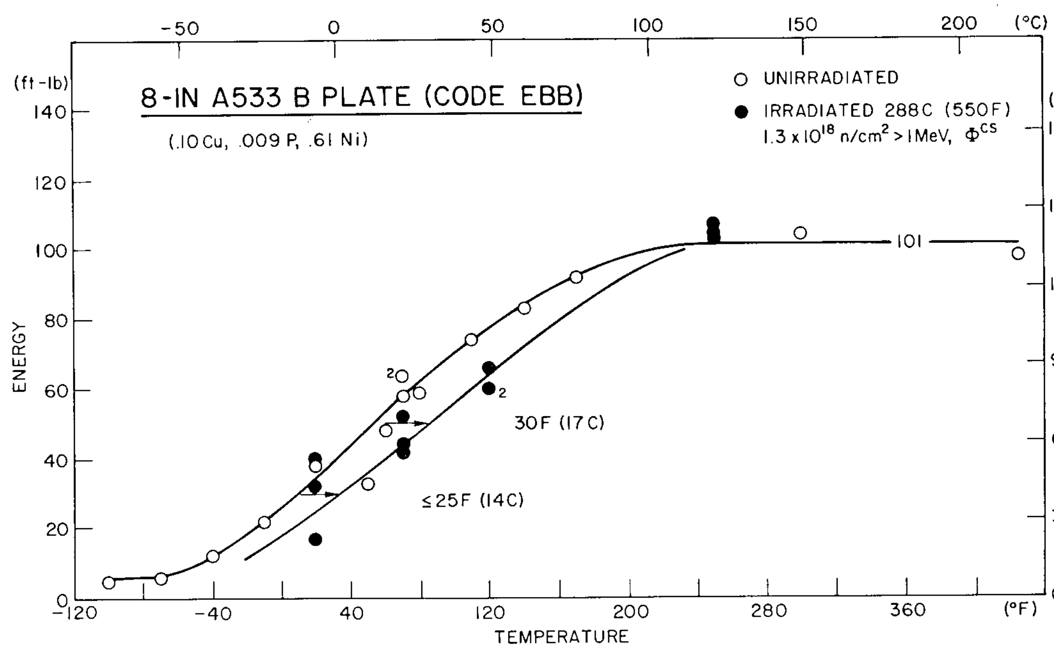

Fig. 3 — Charpy-V notch ductility of the A533-B plate, Code EBB, after low fluence irradiation

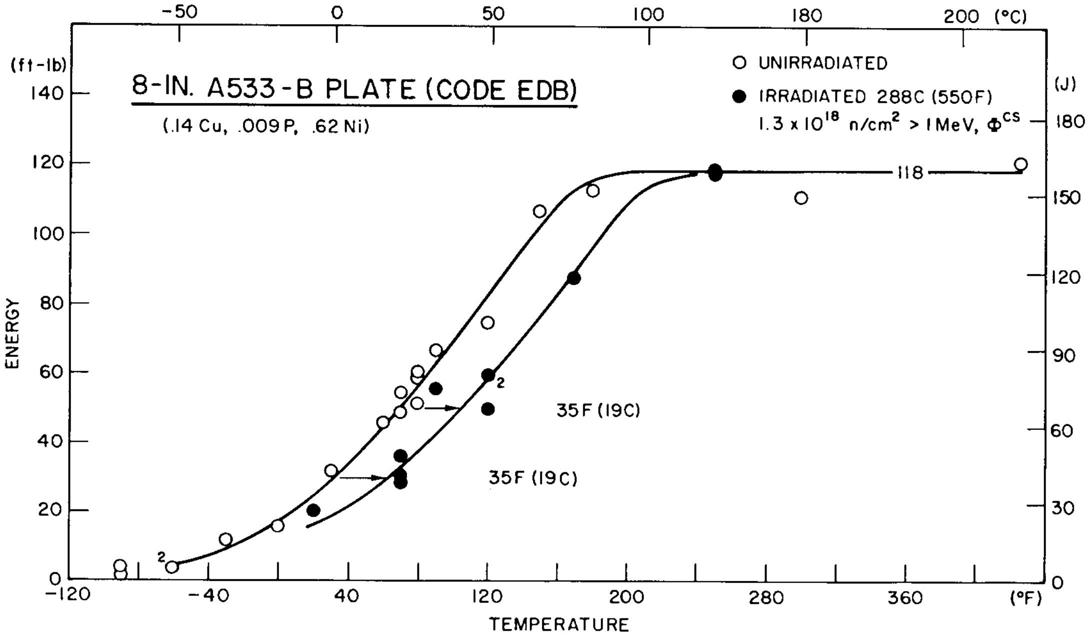

Fig. 4 — Charpy-V notch ductility of the A533-B plate, Code EDB, after low fluence irradiation

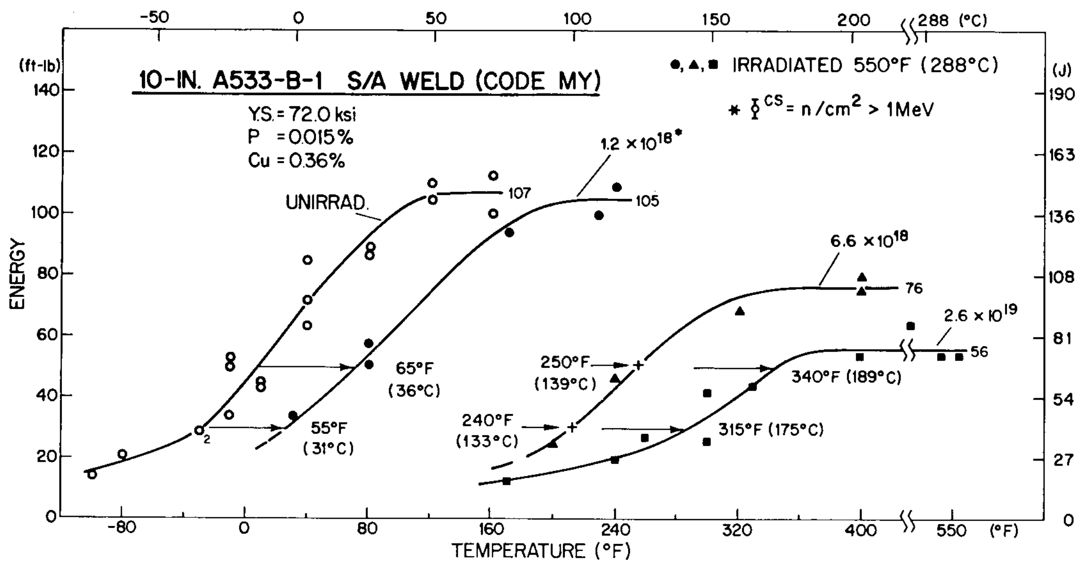

Fig. 5 — Charpy-V notch ductility of submerged arc (S/A) weld, Code MY, before and after irradiation to three fluences

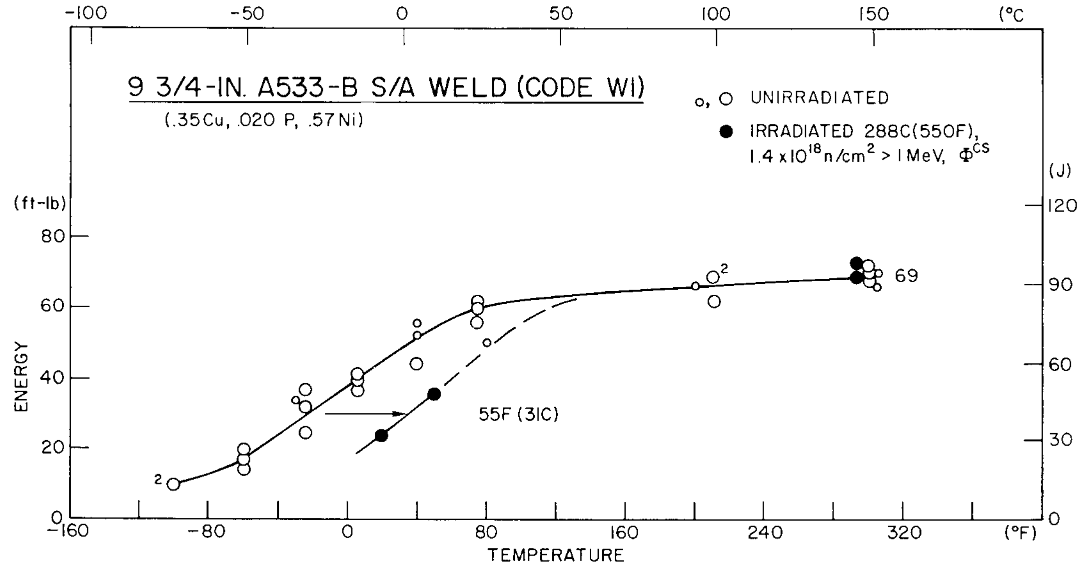

Fig. 6 — Charpy-V notch ductility of submerged arc weld, Code W1, after low fluence irradiation

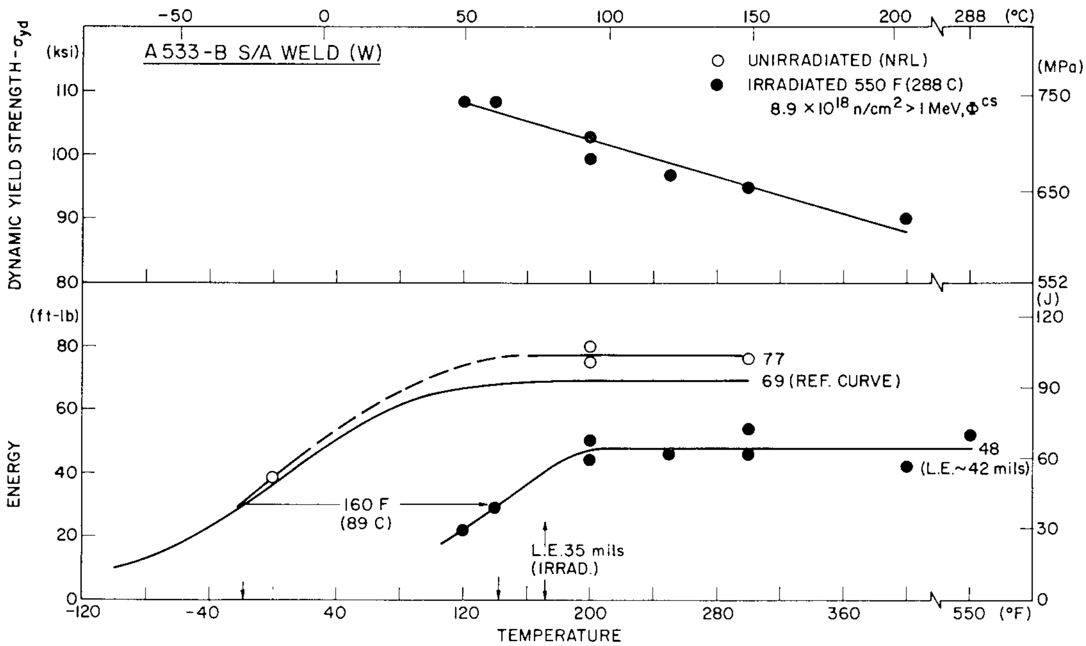

Fig. 7 — Charpy-V notch ductility of submerged arc weld, Code W, after intermediate fluence irradiation. Postirradiation dynamic yield strength determinations from Dynatup load vs time traces are also shown in the upper graph and in Figs. 8 and 9.

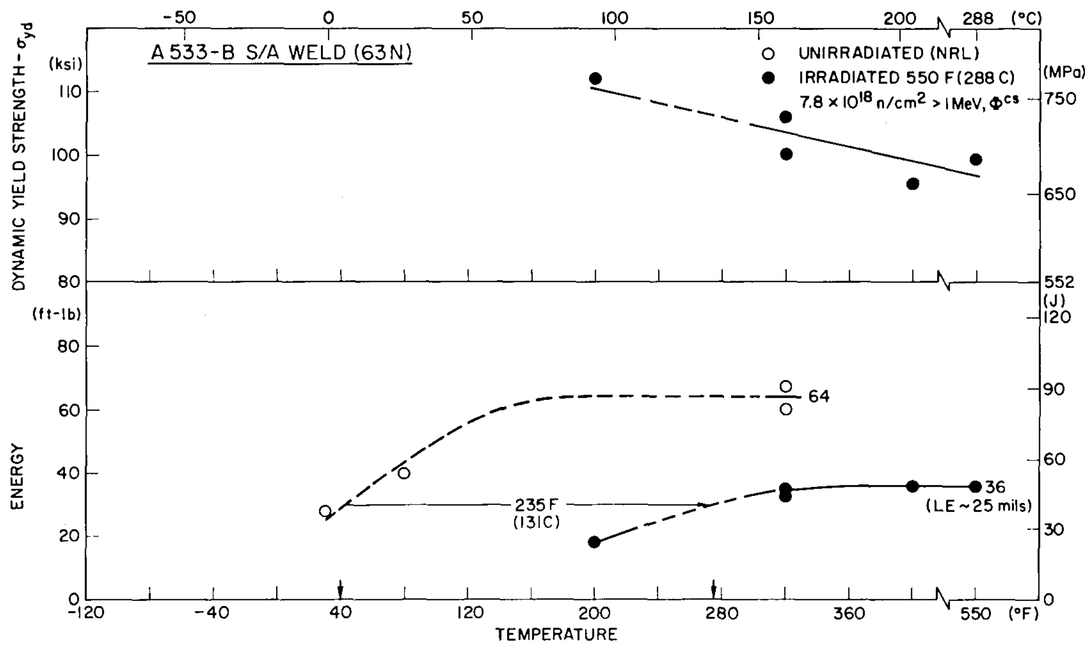

Fig. 8 — Charpy-V notch ductility of submerged arc weld, Code 63N, after intermediate fluence irradiation

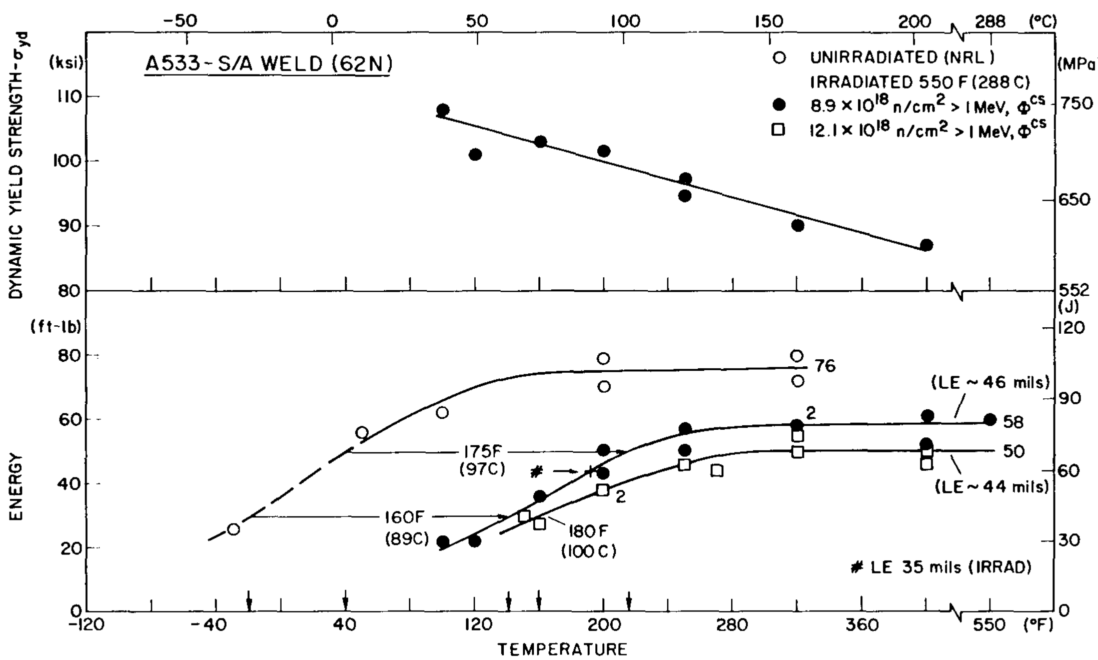

Fig. 9 — Charpy-V notch ductility of submerged arc weld, Code 62N(1), after irradiation to two intermediate fluences

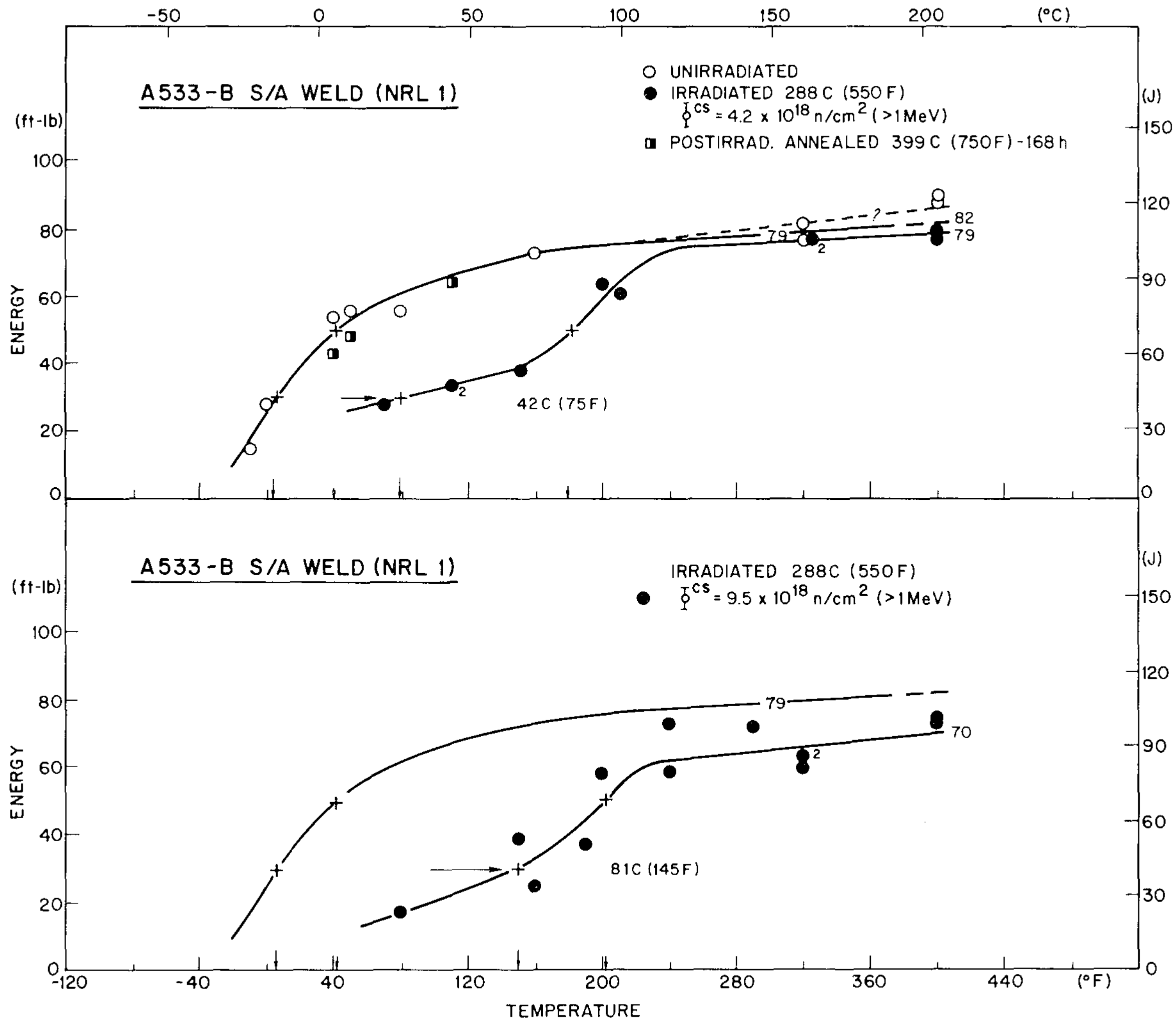

Fig. 10 — Charpy-V notch ductility of submerged arc weld, Code NRL 1, after irradiation to two fluences. Limited results for postirradiation heat treatment are also shown in this figure and in Figures 11 to 17

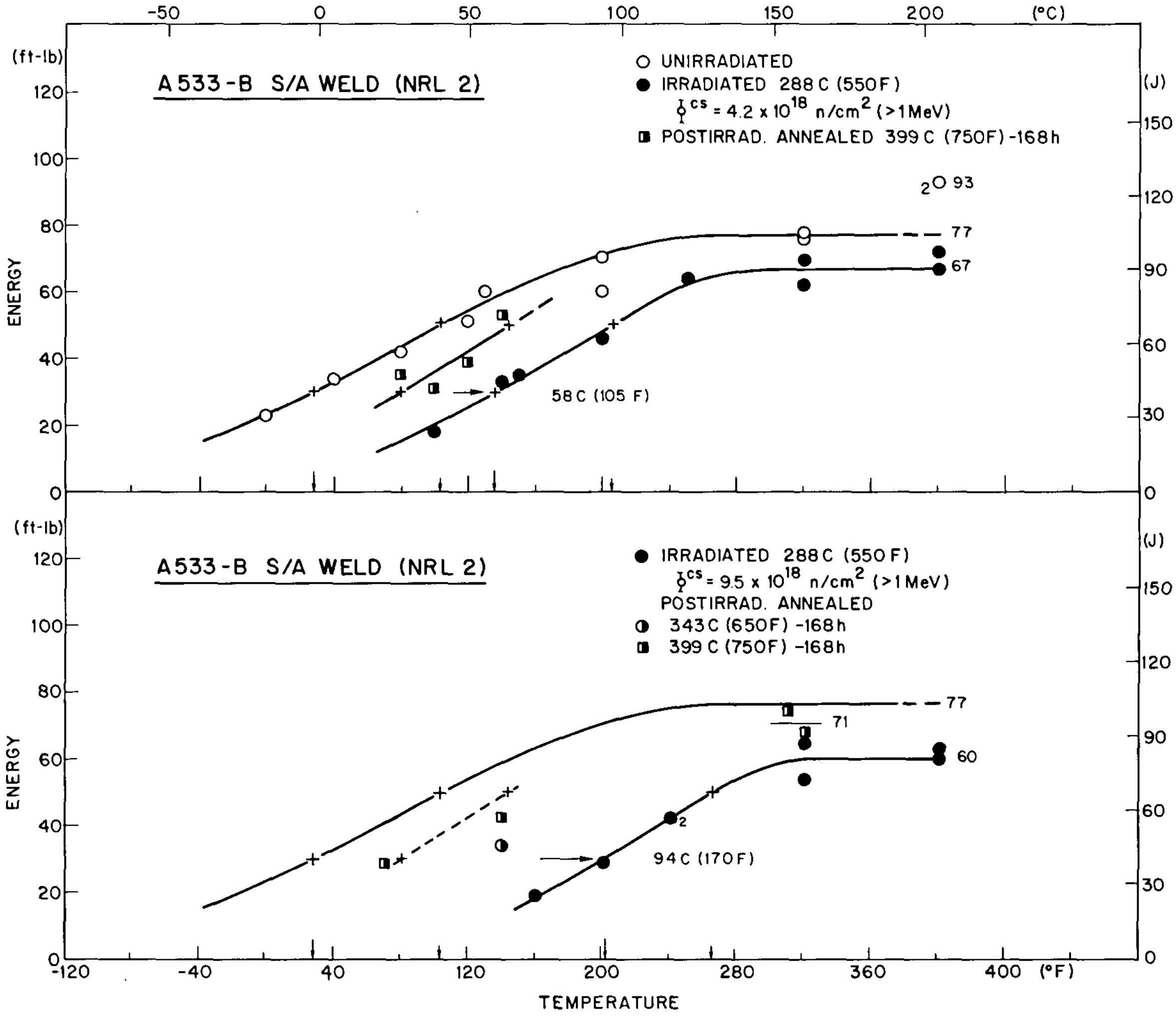

Fig. 11 — Charpy-V notch ductility of submerged arc weld, Code NRL 2, after irradiation to two fluences

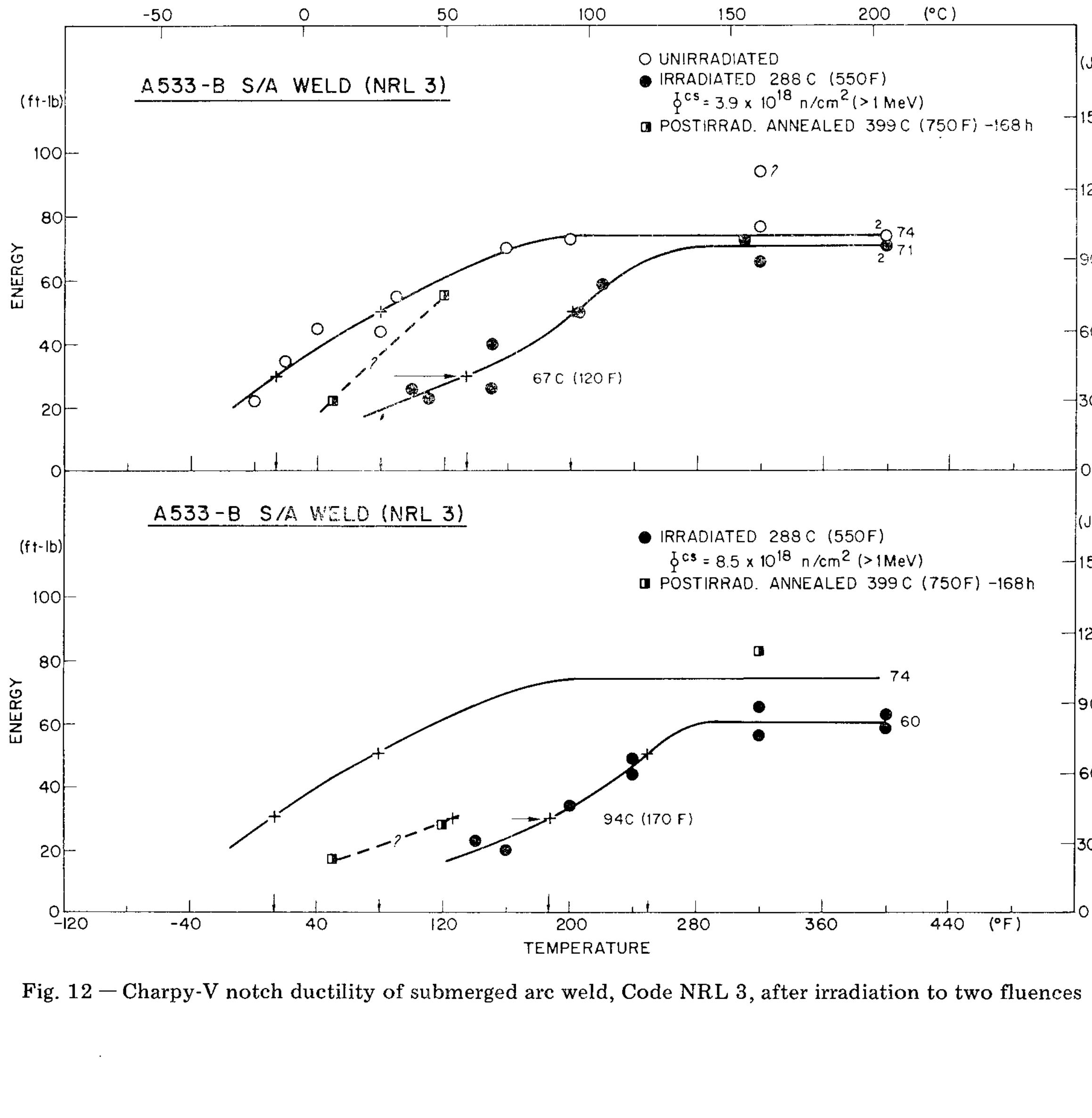

Fig. 12 — Charpy-V notch ductility of submerged arc weld, Code NRL 3, after irradiation to two fluences

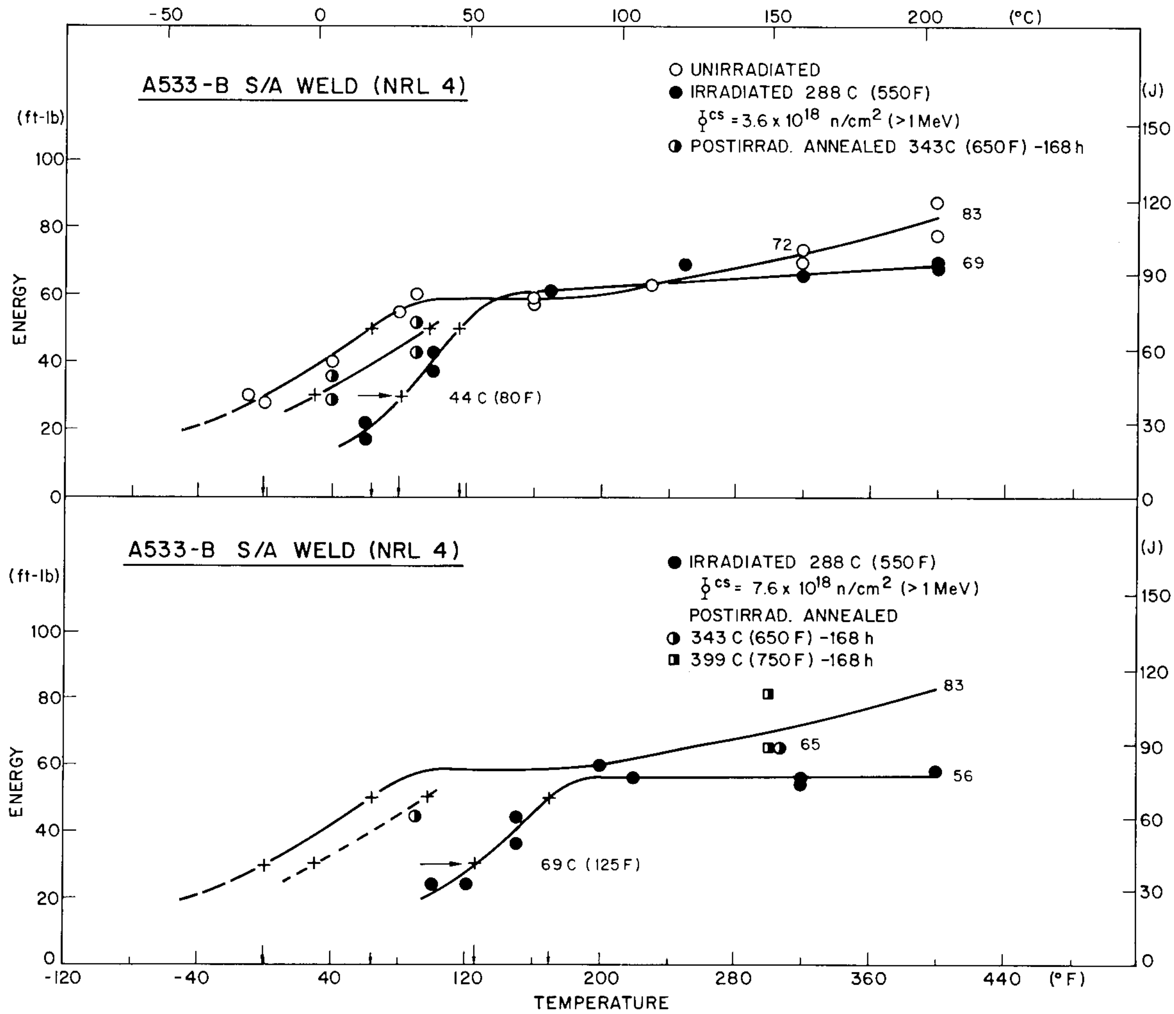

Fig. 13 — Charpy-V notch ductility of submerged arc weld, Code NRL 4, after irradiation to two fluences

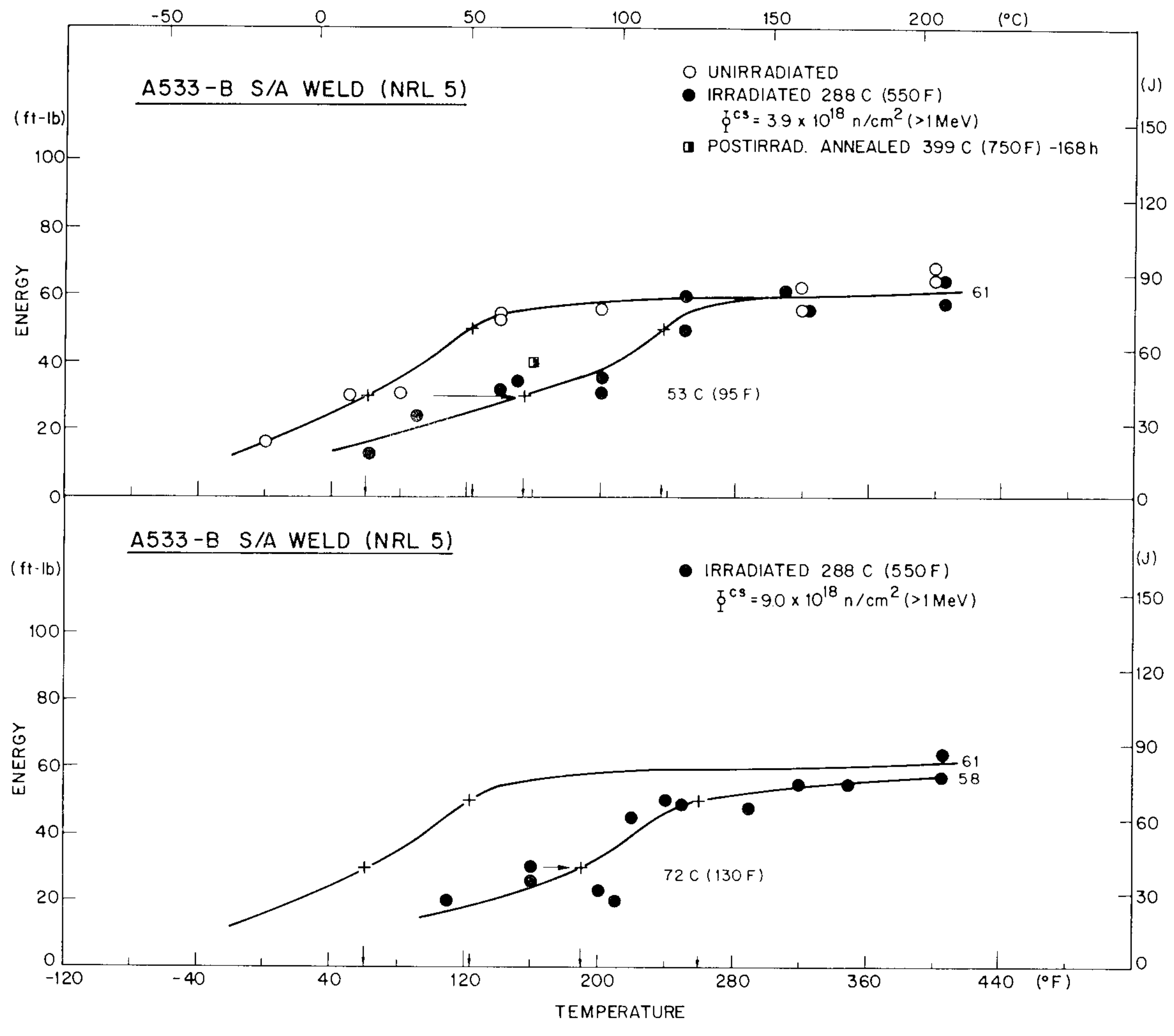

Fig. 14 — Charpy-V notch ductility of submerged arc weld, Code NRL 5, after irradiation to two fluences

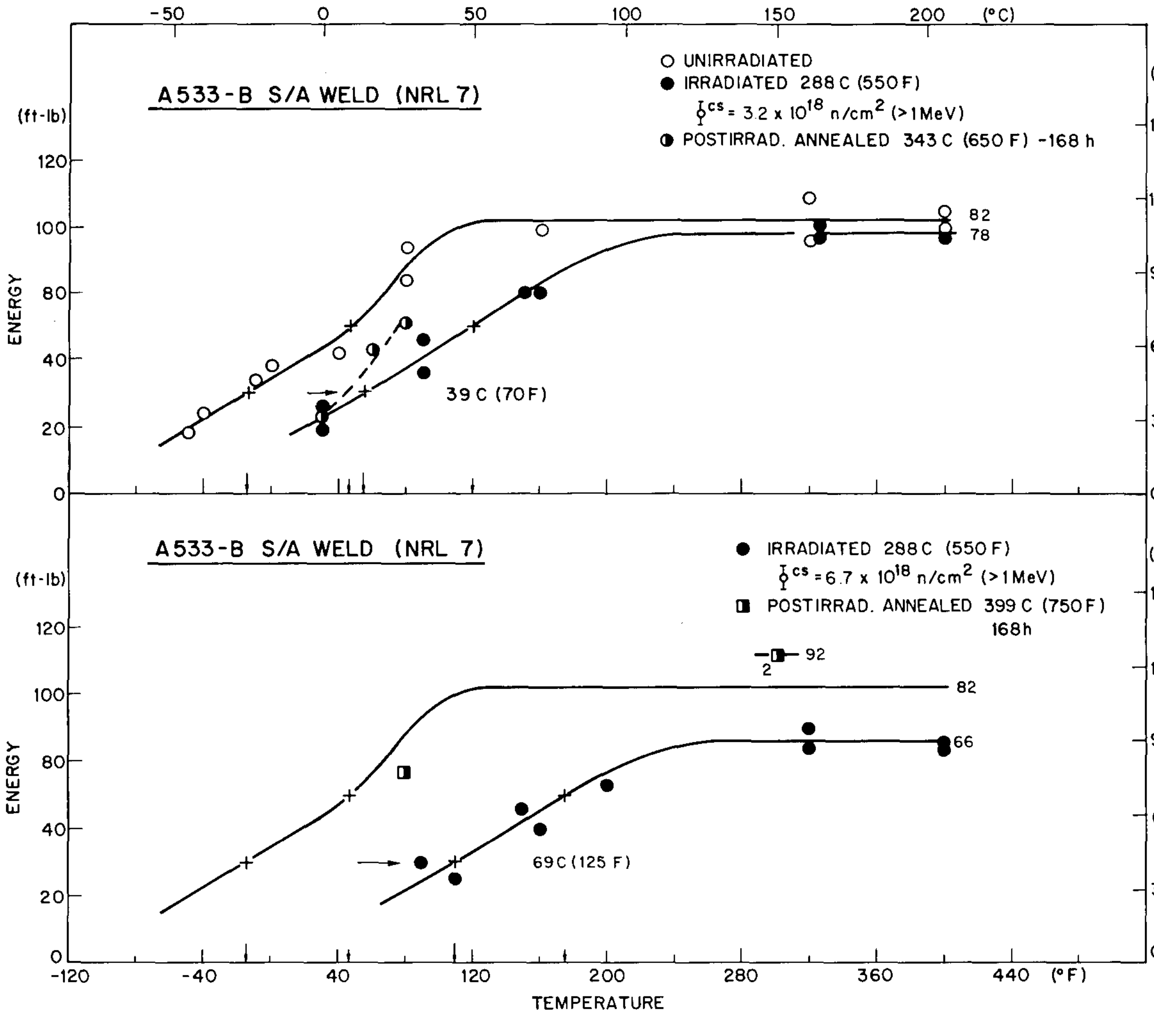

Fig. 15 — Charpy-V notch ductility of submerged arc weld, Code NRL 7, after irradiation to two fluences

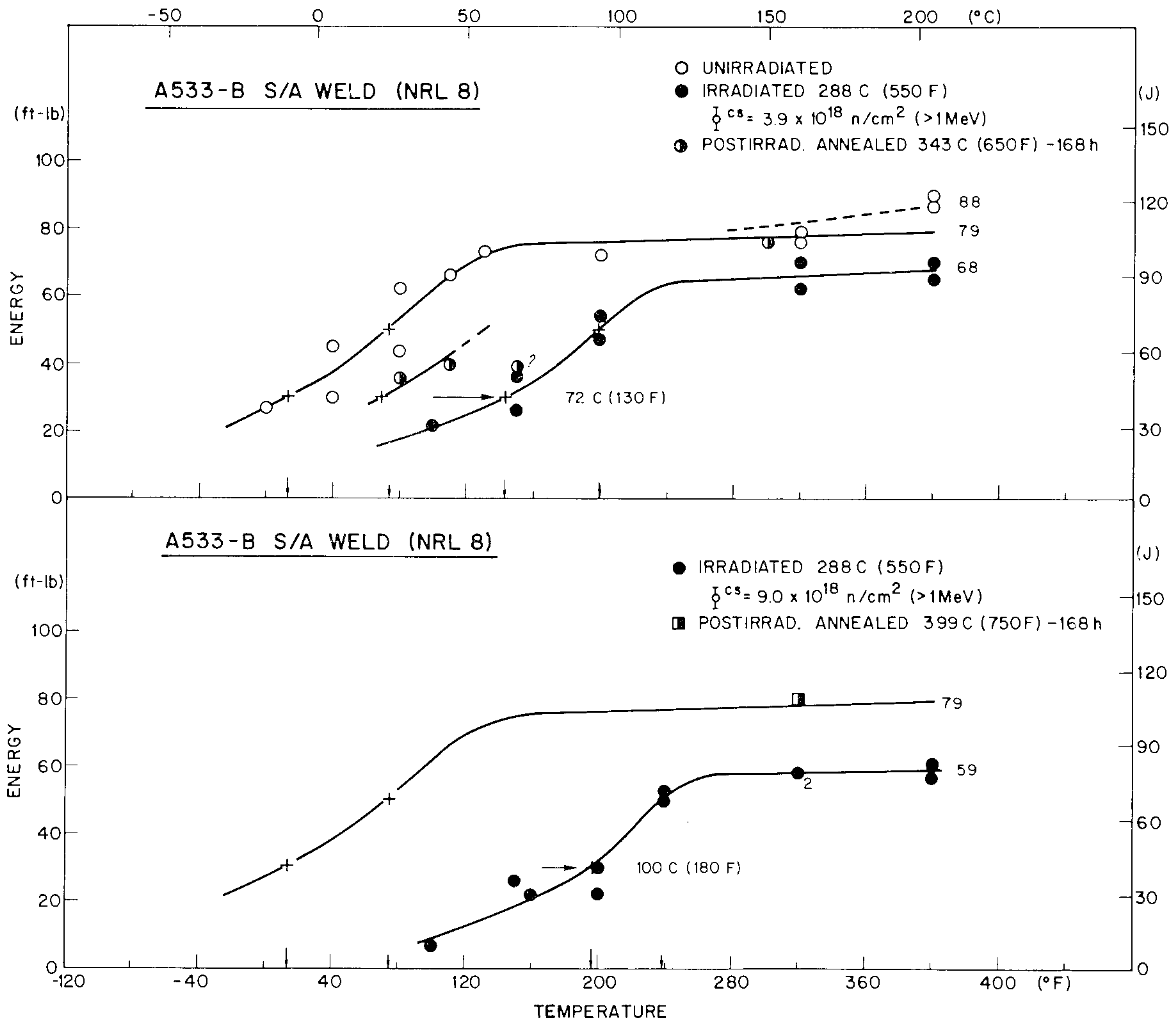

Fig. 16 — Charpy-V notch ductility of submerged arc weld, Code NRL 8, after irradiation to two fluences

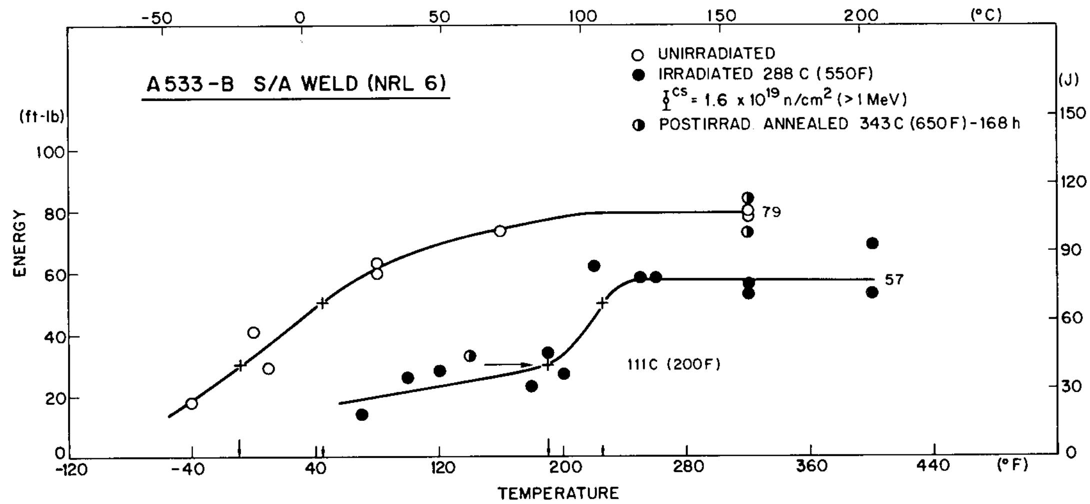

Fig. 17 — Charpy-V notch ductility of submerged arc weld, Code NRL 6, after intermediate fluence irradiation

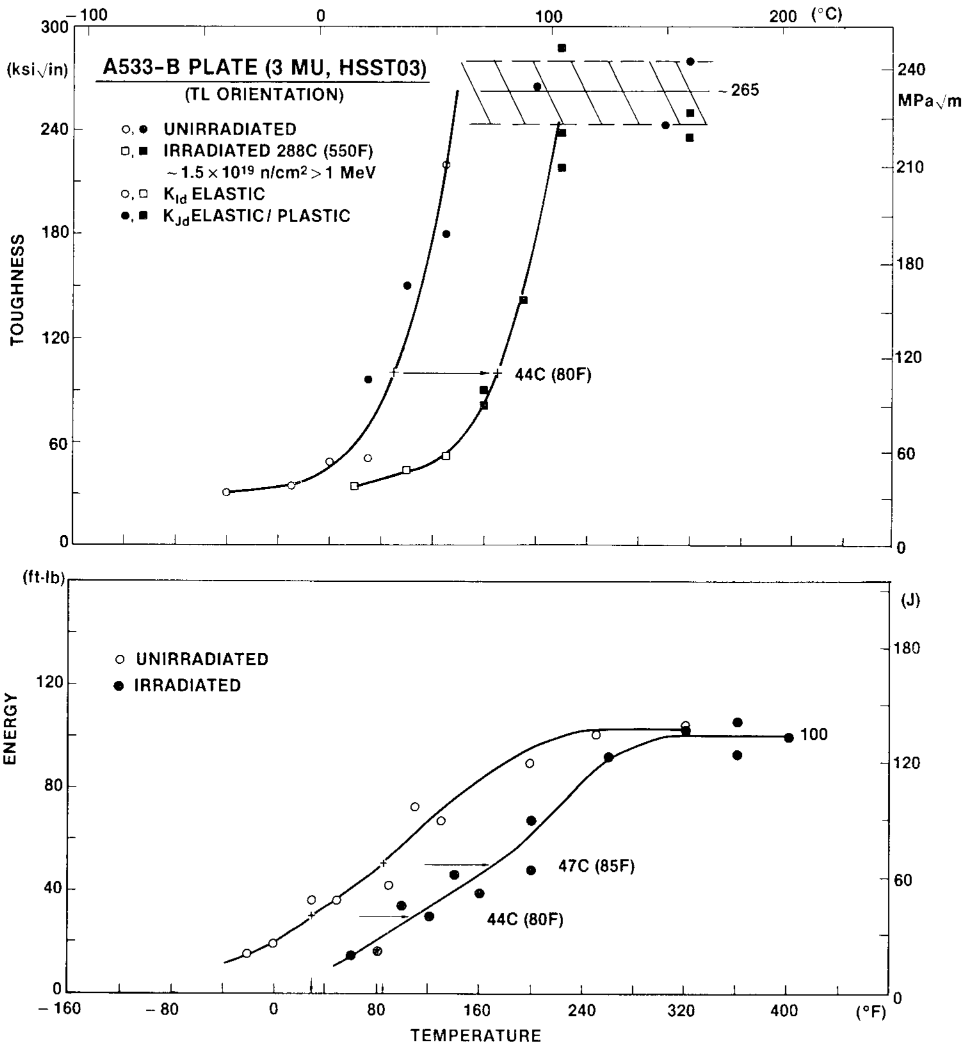

Fig. 18 — Comparison of Charpy-V notch ductility and dynamic fracture toughness for the IAEA A533-B reference plate, Code 3MU, before and after irradiation. Fracture toughness was determined using fatigue precracked Charpy-V specimens and J-integral assessment procedures.

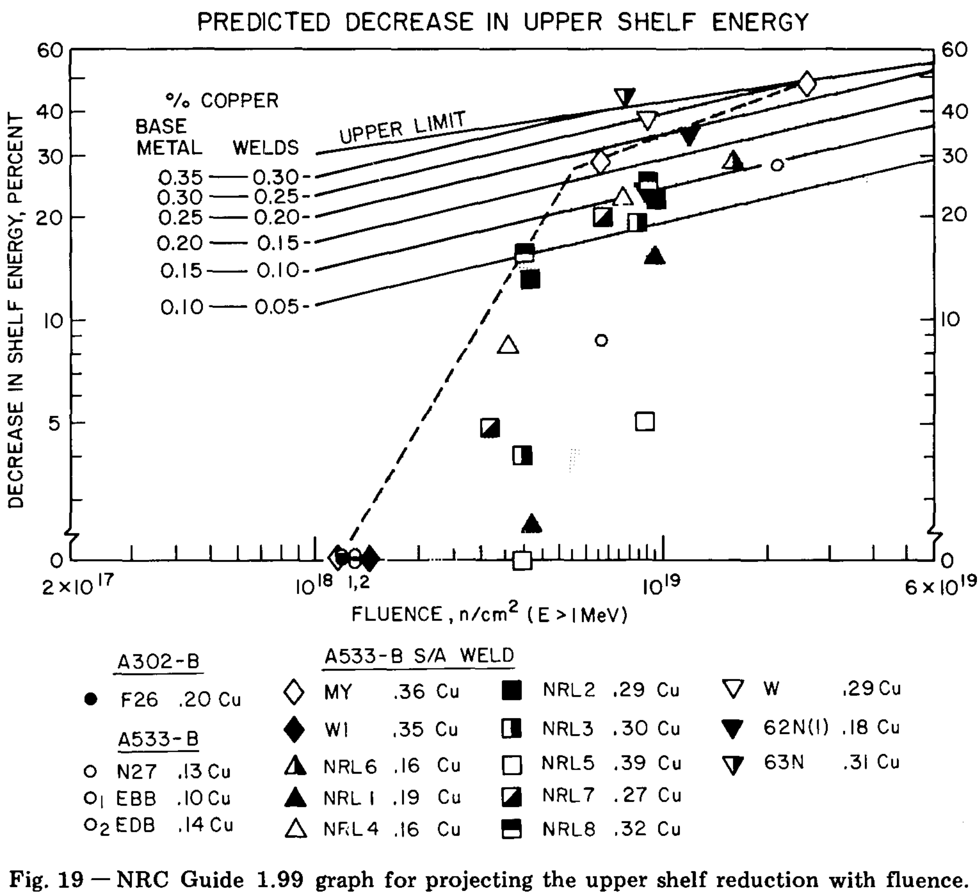

Fig. 19 — NRC Guide 1.99 graph for projecting the upper shelf reduction with fluence. Results of the present study are superimposed. The data suggest that a set of bilinear curves might better describe the upper shelf trend. The dashed line represents the behavior of submerged arc weld, Code MY.

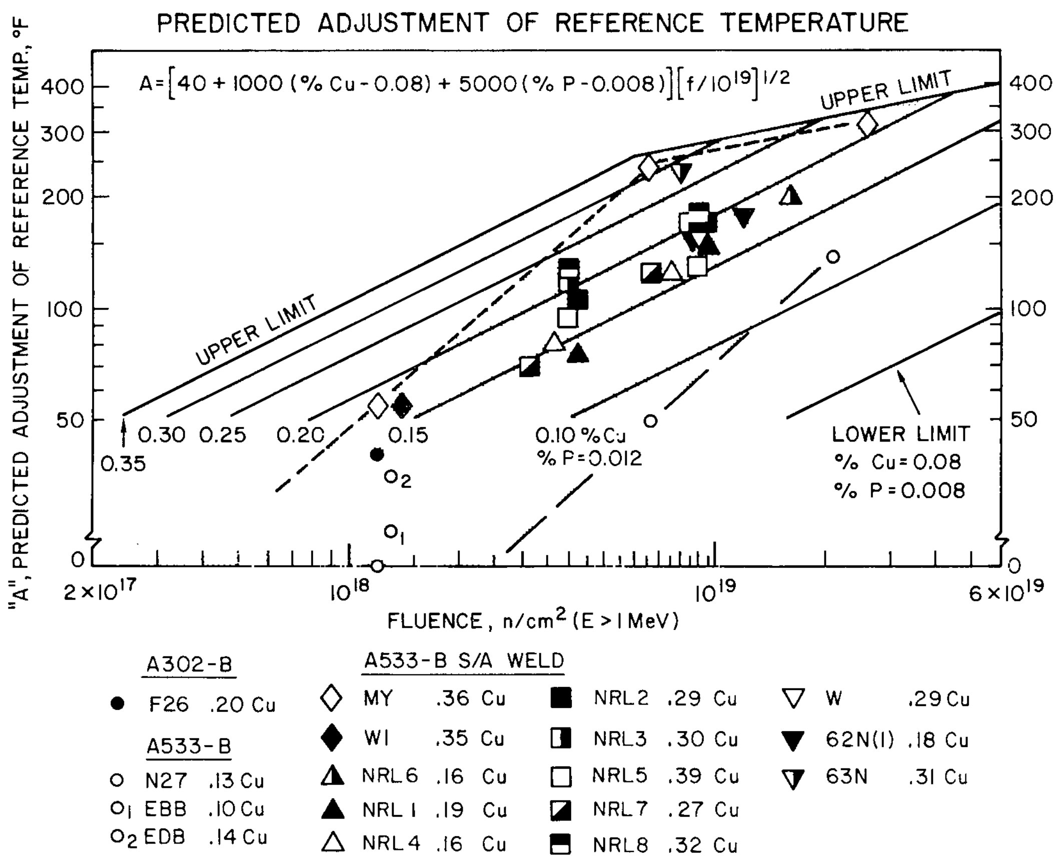

Fig. 20 — NRC Guide 1.99 graph for projecting the reference temperature elevation with fluence. Results of the present study are superimposed. Note the degree of conservatism in the NRC Guide projections at low fluence.

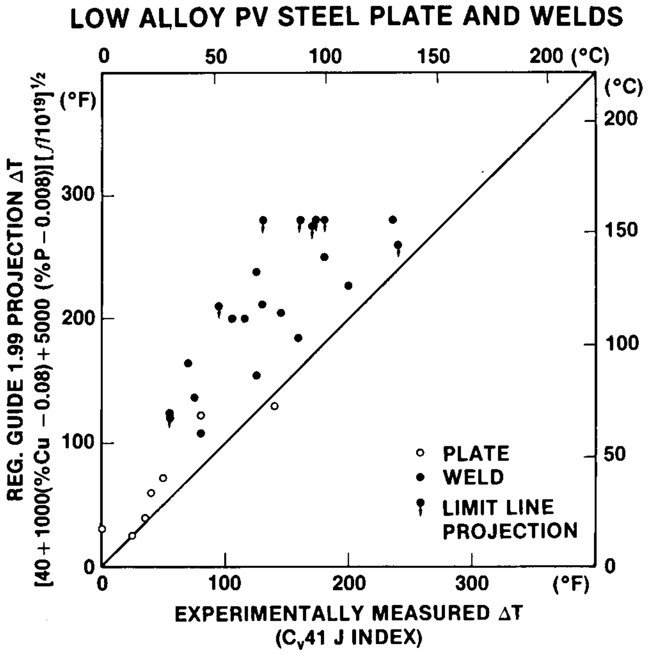

Fig. 21 — Comparison of NRC Guide 1.99 projection of transition temperature elevation with experimental measurement for the individual plates and welds. A wide variation in the conservatism of the NRC Guide projections is noted.